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(54) Thickness measuring apparatus

(57) An apparatus for measuring the thickness of a material 1 comprises a magnet 4 and measuring coil 3 assembly and a magnetically-permeable freely-movable object, such as a steel ball 2, placed on the side of the material opposite from that of the assembly 3, 4, the arrangement being such that the object 2 is constrained by the field of the magnet 4 and the position thereof is sensed by means of the modification of the electric signals in the coil 3 due to the inductive effect of the object 2. An

auxiliary measuring system comprising a non metallic probe 5 which is connected to one part of a two part transducer 7 may also be provided for measuring the distance between the coil and the adjacent surface of the material. Alternatively the auxiliary measuring system may be replaced by a balance unit 12, 13, 14, 15 connected in a bridge with the coil 3, the ball 12 thereof being movable relative to the coil 13 by a micrometer or other measuring device so as to balance the bridge and hence provide a measure of the movement of the object 2.

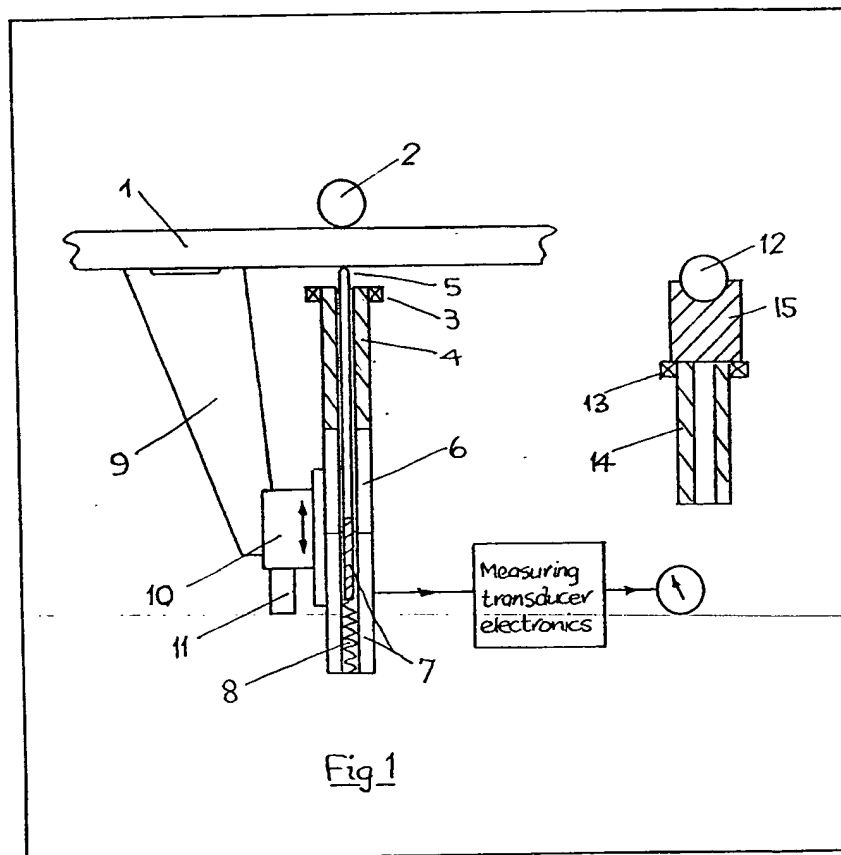


Fig 2

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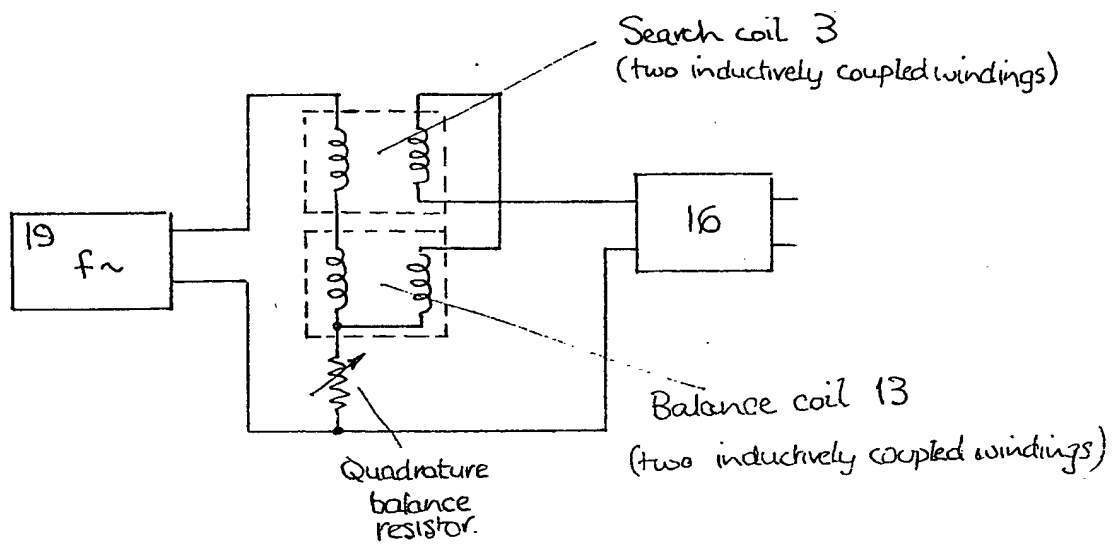


Fig 3

## SPECIFICATION

## Improvements relating to thickness measuring apparatus

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The invention relates to the need to measure accurately the wall thickness of a non-magnetic material in situations where one face of the material is substantially inaccessible to conventional instruments such as calipers. It is particularly suitable where many readings have to be taken, e.g. to produce a thickness contour map.

The principle is to introduce a uniform spherical magnetically-permeable object such as a steel ball to the difficult-of-access side and to control the movement of this ball by a magnet placed on the opposite side of the material whose thickness it is desired to measure, hereinafter called the 'specimen'. The magnet should produce an axially symmetrical field substantially at right angles to the surface to be measured, and by moving it the ball can be made to follow the magnet constrained by the field between the two and to assume an equilibrium position resting on the surface. The effect of gravity in deflecting the magnetic equilibrium position of the ball can be minimised by any or all of the following:—

- (a) operating the device with the magnetic field and gravitational axes parallel, i.e. vertical,
- (b) using a high magnetic field strength to swamp the gravitational effect,
- (c) reducing the gravitational weight by using a hollow sphere or a low-density magnetic material for the ball.

Several alternative effects can be used to determine the distance between the ball and the controlling apparatus on the other side of the specimen, from which the latter's thickness can be derived. These are:—

1. variation in the reluctance of the magnetic circuit with the proximity of the ball (suitable for use with non-magnetic metallic or non-metallic specimens),
2. variation of the inductance of an auxiliary detecting coil with the proximity of the ball by change of permeability and/or by coupling with the surface conductance (suitable principally for non-metallic specimens),
3. variation of the frequency when disturbed of the oscillatory rolling mode of the ball as a function of its distance from the magnet (suitable for use with smooth-surfaced non-magnetic metallic or non-metallic specimens).

These effects can be used separately or in combination as a simple analogue by allowing the polepiece of the magnet, or a short probe rigidly attached to it, to contact the surface of the specimen opposite to the ball and calibrating the resultant electrical readings corresponding to the magnitude of the selected effects in terms of distance  $d$  between the contacting periphery of the ball and the magnet or probe tip, i.e. the specimen thickness. This simple method suffers from several disabilities, however, such as non-linearity, insensitivity and drift, which would relegate it to low-accuracy applications.

A better principle capable of much more accurate

and stable resolution is to reset the distance  $d$  to a fixed value slightly greater than the maximum thickness to be measured and to use an auxiliary linear measuring system to measure the residual distance between the magnet and the surface adjacent to it. By setting the zero of the auxiliary linear measuring system appropriately, direct readout of specimen thickness may be obtained.

By way of example, where the specimen is non-metallic and the thickness is of the order of 10 mm the following method is appropriate. Fig. 1 shows a suitable arrangement. 1 represents the specimen, 2 the permeable sphere in the field of magnet 4. This is shown as a cylindrical permanent magnet with an axial hole to accommodate the non-metallic probe 5 which operates in conjunction with measuring transducer 7 held in fixed relation to 4 by the non-magnetic spacer 6, and is spring-loaded into contact with the surface of 1 by spring 8. Bracket 9, linear drive mechanism 10 and motor 11 together form a means of moving the assembly comprising 5, 4, 6, 7, 8 in relation to the surface of 1 and the ball 2. Search coil 3 is mounted on the tip of magnet 4 and is used to detect the position and/or movement of the ball 2 by measurement of its change of impedance as it approaches or recedes from the ball. The surface of the ball may be plated with silver or copper to improve the discrimination due to eddy-current skin effects.

The tubular magnet may have a deleterious effect on the sensitivity of the position search coil 3 because of the effects of its permeability and circulating eddy-currents. This can be minimised by suitable choice of magnet material and/or the use of laminated construction. Alternatively, the permanent magnet can be replaced by an air-cored solenoid tuned by a parallel capacitor to the search frequency, and fed with stabilised current from a source which has a high impedance at the search frequency. In order to achieve maximum electrical discrimination in the presence of the residual effects of the magnet, etc., an identical structure is used as the other arm of a bridge, the ball in this case being held at a suitable fixed distance from the search coil by the cradle 15.

By way of example, Fig. 2 shows a suitable electrical circuit for the invention. 19 is a source of alternating current of frequency  $f$  feeding the bridge network comprising search coil 3 and impedance 17 as one arm and its identical counterpart coil 13 and impedance 18 as the other arm. Null detector amplifier 16 feeds the in-phase winding of a two-phase induction servomotor (a drag-cup motor is suitable), the 90° reference winding being fed from a suitable 90° output from the signal generator connected so as to drive the rotor in a direction to null the error. To prevent over-correction and hunting, damping methods well-known to those skilled in the art may be used, e.g. by applying a small DC or low-frequency signal whose amplitude increases as the null point is reached, to one phase of the motor by means of a modulator which can be incorporated in 16 (ref. B.P. 663,279).

In use the probe incorporating the measuring transducer is supported by bracket 9, which is either

contd.

in contact with the surface of the specimen 1 opposite to that on which the ball runs or in a stationary relationship to that surface. The servomotor 11 drives the probe assembly including search coil 3 to a fixed distance from the ball, measured through the specimen, determined by bridge balance. As the probe is moved over the surface the ball moves with it, centred by the magnet 4, the separation being held constant by the action of the servomechanism and sensing system. The transducer 7 actuated by probe rod 5 in contact with the surface of the specimen can then be calibrated to read the thickness directly at that position, since its body is being maintained at a fixed distance from the ball, and the thickness may be displayed on a digital or analogue display by a separate electronic apparatus appropriate to the type of distance-measuring transducer selected.

An alternative simplification is to omit the auxiliary measuring system comprising transducer 7 and its associated equipment and to incorporate the measuring means in the balance unit 12, 13, 14, 15. If care is taken to make this in all essential respects identical to the main detector unit and provision is made to move the ball 12 relative to coil 13 by means of a micrometer or other measuring device either manually or automatically until the bridge is balanced, then this indicated ball-coil distance will correspond with that of the main detector, and can be given an exact calibration. In this mode the out-of-balance voltage from the bridge can be used as a convenient indication of thickness variation of a specimen about a mean level indicated by balance.

Although a simple AC Wheatstone bridge has been described in the foregoing this can suffer from drift due to temperature changes when the inductive and resistive components of the impedances 3 and 13 are comparable. To eliminate this disadvantage it is convenient to use a differential transformer arrangement as shown in Fig. 3, which removes the effect of the resistance of the windings from the measurement.

Another distance-sensing mode which can be used as an alternative to that just described, or in addition to it in order to improve the resolution, is to detect the frequency at which the ball oscillates in a rolling mode as it comes to rest under the influence of the magnetic centering force. When the other relevant factors are constant this frequency varies inversely as a function of the separation distance between the magnet polepiece and the surface of the ball. This method of detecting the distance between the ball and the magnet is particularly applicable when the material of the specimen is electrically conducting and non-magnetic, e.g. aluminium, which would shield the eddy-current coupling between the ball and the search coil. No change is necessary in the arrangement of Fig. 1. An alternating voltage will be induced in coil 3 by the oscillating movement of the ball due to variation of the reluctance of the magnetic path. This voltage can be amplified and its frequency compared with a standard frequency by well-known methods.

If the arrangement of Fig. 2 is being used to measure a non-metallic specimen, when the bridge is bal-

anced the input to amplifier 16 will comprise, in addition to the component just described, a suppressed carrier  $f$  modulated by the oscillation frequency of the ball. Either signal may be compared in phase with a standard frequency signal and the signal produced by the phase difference used as a 'vernier' to reset the position of the probe until the frequencies coincide. This vernier correction can be made by means of a separate actuator, or more cheaply and conveniently by arranging the auxiliary signal effectively to take control and modify the null point of the bridge, allowing the servomotor 11 to provide the additional corrective movement.

Although the invention has been described using a magnetic ball because this is the simplest and most maneuverable frictionless object it should not be taken to exclude the use of other magnetically movable objects should there be an advantage in a particular situation. Barrelled cylinders and cylinders making contact with the specimen on a curved end face, lubricated and unlubricated, have proved useful in certain circumstances. A particular use and advantage of the latter is to extend the range of thickness which can be measured by using another magnet as the movable object. For magnets of a given power the useful range can be extended by at least 50% provided that appropriate anti-friction measures are taken, e.g. by using a polished polytetrafluoroethylene skid under the magnet or by oil or air lubrication. If appropriate, the attractive means and the distance-sensing means may be separate, for example by surrounding the magnet by a ring or disc of highly permeable and/or highly conducting material to influence the search field.

#### 100 CLAIMS

1. Thickness measuring apparatus comprising a magnet and measuring coil assembly and a magnetically-permeable freely-movable object (hereinafter abbreviated to MPFMO), such as a steel ball, placed on the opposite side of the material, movement of which object is controlled and constrained concentrically by the field of the magnet and whose axial position is sensed by means of modification of the electrical signals in the coil due to the inductive effect of the MPFMO.

2. Apparatus as claimed in Claim 1 in which the axial distance between the MPFMO and the magnet and measuring coil assembly is adjusted to a fixed value larger than the thickness which it is required to measure, and the thickness measured in terms of the difference between the fixed value and the gap between the magnet and measuring coil assembly and the adjacent surface of the material by an auxiliary measuring system utilising a probe in contact with the adjacent surface.

3. Apparatus as claimed in Claim 1 in which the spacing between the MPFMO and the magnet and measuring coil assembly represents the distance to be measured and is compared with an electrically-identical remote balance unit which has provision for indicating the distance between the MPFMO and the measuring coil.

4. Apparatus as claimed in Claims 1 and 2 in which the separation between the MPFMO and the magnet and measuring coil assembly is determined

by the frequency of the signal induced in the measuring coil by the mechanical oscillation of the MPFMO as it comes to rest under the influence of the field of the magnet.

- 5     5. Apparatus as claimed in Claims 1, 2 and 3 in which the adjustment of the separation between the MPFMO and the magnet and measuring coil assembly is accomplished by means of a servomechanism operated by the out-of-balance signal from the  
10 bridge or differential transformer which forms part of the measuring system.

6. Apparatus as claimed in Claims 1, 2, 3, 4 and 5 in which the MPFMO is a cylindrical or barrel-shaped magnetically-permeable object in a rolling mode.

- 15     7. Apparatus as claimed in Claims 1, 2, 3, 4 and 5 in which the MPFMO is a purpose-designed sliding object incorporating the following parameters either singly or in combination: high magnetic permeability, high electrical conductivity, permanent magnetism, solid or fluid lubrication.  
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